

Inquiry: The University of Arkansas Undergraduate Research Journal

Volume 13

Article 10

Fall 2012

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Recommended Citation

Newsum, Michael Jake (2012) "Investigating 3 Axis CNC Processes for Creating 3D Objects," *Inquiry: The University of Arkansas Undergraduate Research Journal*: Vol. 13 , Article 10.

Available at: <http://scholarworks.uark.edu/inquiry/vol13/iss1/10>

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INVESTIGATING 3 AXIS CNC PROCESSES FOR CREATING 3D OBJECTS

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Abstract

Using 3 axis CNC (computer numerical code) routing processes of the Visualization Lab, the CNC was tested for 3D object milling. The CNC process was designed for manufacturing 2D cut out objects with or without a 3D surface. The processes of modeling the object, using CAM (Computer Aided Manufacturing) programs, producing the Toolpath, post processing, editing G Code, positioning the stock material, and setting the machine origin were tested for an understanding of what changes had to be made to the process to accurately mill and cut out 3D objects. Solutions were discovered through digital and physical setups that are designed to reference one another accurately through CNC. The process of designing the digital object in the Rhinoceros 3D modeling program became the way in which the Toolpaths were designed to produce the physical object as well as the means of material attachment and indexing, thus allowing 3D object creation.

Introduction

3 axis CNC routers are machines that use Computer Numerical Code (CNC) to control milling in the X Y Z directions. This code is commonly generated by a combination of CAD (computer aided design) and CAM (computer aided manufacturing) programs that require a postprocessor to communicate the right commands as a tool path for the CNC. This process is used to automate machining for production of 2D cut out objects and 3D surfaces. In order to design and create 3D objects with a 3 axis CNC, the process of production and design must be integrated, so that the limitations of the machine can be used as a framework to understand how the object can be produced.

To expose the limitations of 3 axis routing a sphere was selected to test the manufacturing process. A sphere will require a variety of milling procedures, such as leveling and drilling with flat end mills, as well as roughing and surfacing with ball end mills. The Toolpaths will have to synchronize in order to create one continuous surface from top to bottom. To do this, the tool lengths must be accurately set with each tool change, the stock material needs to be repositionable, and the Toolpaths have to reference the output surface of previous and future Toolpaths.

It was assumed from the onset of this research study that the process would require milling the stock material in multiple orientations, such as rotating the stock in the XY, XZ, or YZ plane. The relationship between the router's origin (X, Y, Z) and the stock material's placement on the router's table must not only match the digital representation, but the stock must also be removed and replaced as digitally represented. Milling the top half of a sphere into the stock is relatively easy; however removing the stock and reattaching it so that the second half sphere lands on top of the first half relative to X Y and Z proved to be challenging and unreliable.

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A physical X Y origin reference was made and attached to the machine's table to precisely attach the stock (Figure 1). The physical origin was made of plywood, so that if it was hit while milling it would not damage the end mill. The physical origin is also strong, inexpensive to make and easy to produce. The shape was designed to be an L, so that the X and Y axes are extended. The physical origin was milled on the CNC to ensure accuracy. The interior corner of the L was cut out so that the stock material could sit flush with the two interior surfaces of the physical origin. This process makes the machine's origin corner and the X Y axis physically represented for aligning the stock material. If the stock material is precisely cut out as digitally represented first, then the stock can be positioned accurately in multiple orientations (Figure 2).

**Figure 1****Figure 2**

A problem with the physical origin is that it cannot be attached to the table without the machine specifying where it belongs. If it was attached first, the X Y relationship would not be precise, and since the interior corner is cut away, the machine's origin cannot be set to the physical origin. A simple solution was to set the machine's origin, and then mill the placement of the physical origin.

Attaching the L to the CNC table made reattaching a part easy but only in the original milling position. The stock could not reliably be rotated or flipped because of the tolerance in the hand positioning of the physical origin. For example, if the origin is $-1/32''$ off in X and $-1/16''$ off in Y when the stock is rotated 90 degrees clockwise, the second Toolpath would be off by $+1/32''$ in the Y direction and by $-1/16''$ in the X direction. Therefore, with one clockwise rotation, the offset of the physical origin in the X and Y direction on the first Toolpath becomes $X \text{ offset} = X+Y$ and $Y \text{ offset} = X-Y$ for the second Toolpath. If rotated again, as expected, both the original x and y offset will multiply by -2, and when rotated a third time it will be the inverse of the first rotation. If the material is flipped instead of rotated, the offset will just multiply by -2 for the axis, which rotates while the other retains its relative position. The hand tolerance is very low when positioning, which makes this distance very hard to measure and digitally calibrate. In comparison with the high levels of accuracy given by the CNC, this process of attachment was not precise enough.

Using the CNC to place the physical origin is the only way that the physical origin could have the same low tolerance of the CNC. Since the CNC router cannot move the L, the original physical origin was redesigned. The second origin representation recognized that if the stock is pre-cut to be precise, then the origin is not restricted to being represented at one specific corner but could be placed at multiple corners. This origin representation led to the understanding that if

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the origin could be represented at multiple places then it could make a network to provide attachment to the table.

The process of placing the material accurately also attached the material to the CNC table. By milling holes in the table, pegs could be inserted to fit around the stock material after the stock had been cut to size. The CNC can be used to make holes that are very precise, easy to use, and can be made for any stock. The pegs do most of the work, including holding the stock in place and positioning. This frees the top of attachment clamps, thereby minimizing the left over material from the stock surface.

Using the peg to place the stock, the first Toolpaths were allowed to mill surfaces into the top and bottom of the stock with repeatable accuracy. The first full spheres were then tested to determine if the flipping and rotating setup was successfully implemented. When using the Rhinoceros 3D modeling program to create the half sphere to drive the Gibbs CAM's Toolpath generator, problems arose. This program, like most CAM programs, needs a post processor to turn the Toolpaths into G Code to operate the CNC. The CNC was undergoing an overhaul which left it without an up-to-date post processor. This led to a necessary opportunity to research G Code in an effort to understand how to tell the machine where to move. By testing generic posts within the CAM program, reading about G Code, and drawing optimum machine movements to make accurate 3D surfaces, a postprocessor was edited to be compatible with the CNC.

The CAM program has different types of Toolpaths to select from; they can then be edited to craft the physical representation of the digital object. When making the Toolpath for the half sphere it was observed that the Toolpaths could not accurately represent any object. If the lace cut method is selected, which is common in our daily practice, lines are drawn on the digital surface in raster, radial, or spiral organizations.

When using the raster Toolpath, parallel contours are draped across the surface; their spacing is determined by the Toolpath's step over, which is the distance between each parallel line that drives the tool. The distance from the origin to every edge must be divisible by the lace cut's step over value. If not, the remainder from the tool's specified step over, relative to the distance to the edges of an object, will directly affect how far off the product will be once milled. For example, if an edge of a surface was 0.75" from the origin in the X direction and the tool's step over is set to 0.1" in the X direction, then the edge would be milled at 0.8" from the origin, which is 0.05" off. But, using the same framework, if there was an edge 0.75" from the origin in the Y direction, then the edge would be accurately cut. This is because the Toolpath is only recognizing depth changes along each step over's contour, and the contours collide with the edges in the Y direction when the step over is in the X direction. While the step over could be decreased, thereby increasing accuracy, this is not time efficient. Decreasing the step over is primarily used to increase the accuracy when surfacing.

The radial Toolpath was then tested, since the edges would have more opportunities for collisions. The problem found with this Toolpath was that when making the half sphere, circles were generated that offset a specified step over distance from a specified center point in the X Y orientation. These circles are projected onto the sphere. Although the circles are offset is the same distance, once the lines are made into contours the spacing of the lines on the surface will always consist of a gradient of steps from smallest to largest in the Z direction. The top will have the tightest spaced steps, and the sides will have the largest because of the slope of the surface. This means that the sphere would be much smoother towards the top of the sphere while more stepped at the sides.

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The Spiral Toolpath lent similar results, since the lines were generated in a spiral from the center extending to the outside of the sphere. As the lines went farther from the center, they also became farther apart. This meant that the sphere would have a tight smooth surface at the top and a more ribbed surface towards the center. These Toolpaths may have been in Gibbs CAM's advanced milling procedures, but they needed to advance more, so that the Toolpaths could adapt to the object in order to produce the desired product, regardless of the object or its curvature or edge conditions.

Within the 3D modeling program Rhinoceros, which was used to make the half sphere, there is an associative modeling plug-in called Grasshopper. With the Rhinoceros plug-in, the digital object can be linked so that Grasshopper can extract information from the object, which can be run through a predetermined script that is completely open and written by the user. While these scripts are used for many modeling purposes, they may also be used for making any type of Toolpath from the linked surface. In Grasshopper different Toolpaths from CAM programs were recreated while leaving the code open for user preference modifications. This allowed the sphere to have a circular offset Toolpath that had a gradient of steps in the X Y and Z orientation in order to minimize the number of steps needed to create a smooth surface from side to side. The steps are regulated by a graph that is editable by the user and that allows the user to design the surface texture that is the result of the Toolpath. This also allows for the edge conditions to be accurately represented. The distance from the center to the edge would be divided by the desired step over. The quotient is rounded up, and then this number would be used to divide the distance from the center to the edge to give the recalibrated step over. For example, the edge is 0.75" from the center and the desired step over is 0.1"; therefore the quotient is 7.5 steps, which is not possible. Rounding 7.5 up to 8, then using it to divide into 0.75", gives the recalibrated step over of 0.09375", which will accurately cut the edge. This method is used in Grasshopper to draw lines to the edge, and then to divide the lines into their calibrated step over distance. New lines can then be drawn through these division points, thus making dynamic Toolpaths where the step over is constantly able to change depending on its relation to the position on the surface being milled.

The lines that are projected onto the surface would not make the desired surface if milled. Since the end mill has a thickness and the line represents the bottom center of the end mill, these lines would cut the top of the sphere well, but as it got further down the end mill would plunge into the desired surface, making the sphere too thin. If the sphere was to be 3" in diameter and the end mill was 1/4", then the sphere would end up 3" tall and 2 3/4" wide because half of the end mill would be gouging into the sphere by the time it reached the center. The lines must be calibrated to represent where the tip of the tool should be to make the desired surface. By putting points on the lines, the points can be used to extract information about the surface at that point. Each point used the normal vector of the surface at its location of the point to move each point to its recalibrated location. Then, lines were redrawn through the points to make Toolpaths that recognize how the bit should cut the material.

The lines generated on the surface in the 3D programs can be used as Toolpaths for the CNC router with a tool, developed by Edmond Harris of the University of Arkansas Math Department, called CAMel, which runs within Grasshopper (Harris, 2011). As an open source tool, it is free to use and edit. This tool places points on the lines it is given at a user-defined resolution. These points then use their (X,Y,Z) coordinates to be rewritten into G Code, and the user is the post processor. This allows the designed object to influence the way the Toolpath

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lines are drawn and the G Code generated in real time, while still allowing the designer to interject at any point in the process and customize the way the object should be made.

The lines used to mill the two halves of the sphere completely remove the sphere from the stock material. This would leave the 3D object unprotected from the router while it is moving at very high speeds. It would also not fully cut the surface of the object before it is released, because the sphere is best milled with a ball bit. When the ball bit mills the first half of the sphere, the last cuts uses the side of the end mill, since the sides of the sphere are practically vertical. Once flipped and milled again, the second half sphere releases when the tip of the bit penetrates the stock touching where the tip of the bit reached during the first pass. At this point in the Toolpath, the surface will still have a rib that wraps around the sphere where the end mill did not have a chance to get deep enough to use the side of the ball to take away the vertical remainder of the stock.

Cut out Toolpaths were then designed for the 3D surface. The last line of the Toolpaths for the top and bottom surfacing, which would detach the sphere from the stock, was removed from the Toolpaths. These lines were then used to make a cut out sequence involving 3D tabs made by section cuts through the object and the stock. The cut out line was divided into segments to communicate with the router when to stop and when to start cutting the object away from the stock in order to make tabs. These tabs can be edited in depth, number and thickness for material necessity.

Once the origin is set, the material is placed, the Toolpath is drawn to represent the digital object, the stock is flipped, and the object is cut from the stock; then the sphere is tested to reveal the qualities of the process. For this research study, the tests were very close, however much like the earlier objects there were still inaccuracies somewhere in the process. For instance, the sphere had an offset in the Y direction each time it was milled (Figure 3 and 4). The Toolpath was edited to be more precise and the pegs used to hold the material were placed more carefully; however the sphere's two halves did not line up.

**Figure 3****Figure 4**

As a result, the process of attachment was re-modified. This time the pegs were placed within the remainder of the stock in the corners where the router did not need to mill to make the sphere. This made the attachment much stronger and the alignment much better. This also made it possible for the stock material to be any size when the process starts. The first attachment of the stock to the machine no longer has to be exact. Once the first Toolpath cuts the holes in the stock for the second placement and levels the top surface, the stock can then be reliably flipped

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and set into the holes milled into the table from the same origin. This made the peg attachment much more precise since it was not determined by the materials' outside dimensions (Figure 5, 6, 7, 8 and 9).

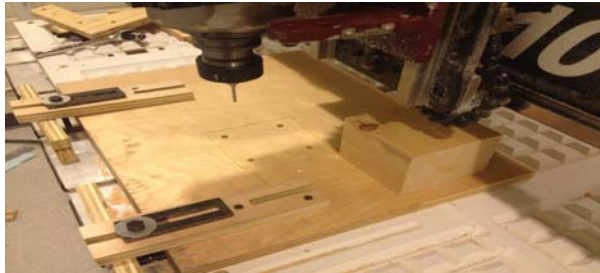


Figure 5



Figure 6



Figure 7



Figure 8



Figure 9

The sphere was milled again, and the results were overall the same. The surfaces were very precise according to their own orientation; however relative to each other the surfaces did not fit (Figure 10). The problem was not in the physical setup; it was a digital issue. For similar reasons that the Gibbs CAM and other CAM program's generic Toolpaths would not accurately make surface edges, the distance between points placed on the lines in CAMel are limited in spacing without referencing the object. The points put on the Toolpath lines in CAMel were spaced by a used defined distance, which would inevitably leave a remainder. The points on the circles are evenly spaced, but they do not necessarily line up with the circles before and after; more importantly, the points around a circle will not always be symmetrical. If every circle is divided to have points every 0.1", some circles will end with smaller segments, meaning that the first point on the line is not in alignment with the point in the middle of the line when cutting through the center. When milling the circle, the Toolpath will not be symmetrical because more material

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will be cut away between points at the center of the line than at the start of the line. While this is not a cause for concern when milling one surface, like everything in the process of milling 3D objects, the tolerance is magnified. In addition, when the stock material is flipped, the original Toolpath is mirrored in plan. By mirroring the digital half sphere after the first Toolpath is made, then re-linking the surface to Grasshopper and CAMEl, the Toolpaths lined up when milling the sphere (Figure 11).



Figure 10



Figure 11

Discussion and Implications

The physical offset was a digital problem only revealed by accurate material placement. When using any of the CAM programs problems arose, but with CAMEl in Rhino-Grasshopper a code will be written to change the way points are placed so that when milling symmetrical objects it will generate symmetrical Toolpaths. Using tools within the design framework allows the design process to extend into the process of making.

This has advanced the process of production and the level of craft on the 3 axis CNC router for the University of Arkansas, Department of Architecture VIZ Lab. The process of milling fully 3D objects has been developed for experimental production (Figure 12 and 13). New design ideas often require new processes of making. This process can go far beyond making simple spheres and symmetrical objects. With an understanding of how to use and manipulate this process, anyone can design 3D objects that can be made on a common 3 axis CNC router.



Figure 12



Figure 13

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Reference

Harris, E. (2011). CAMel Plug-in. [Apparatus]. Fayetteville, Arkansas: University of Arkansas.